RAMGEN POWER SYSTEMS-SUPERSONIC COMPONENT TECHNOLOGY FOR MILITARY ENGINE APPLICATIONS

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ABSTRACT

Ramgen Power Systems, Inc. (RPS) is currently developing two high efficiency gas turbine engine concepts to create two entirely new gas turbine engines. The superior efficiency results from: (1) high pressure shock wave compression and supersonic expansion phenomena that produce high component efficiencies and (2) a unique configuration that minimizes flow stream turning losses throughout the engine. The RPS engine concept can be configured as a high-pressure ratio simple-cycle design for propulsion applications or as a low-pressure ratio recuperated engine. The RPS engine can be applied to a mobile power plant (such as military propulsion system for future combat systems), to a stationary power generator (such as a standalone power-only mode device), or to a fuel cell in a hybrid configuration. This paper presents the development of the RPS gas turbine technology and potential applications to the two specific engine cycle configurations, i.e., an indirect fuel cell / RPS turbine hybrid-cycle, and a simple-cycle turbine. The system promises a Specific Fuel Consumption (SFC) equal to or better than the SFC of current reciprocating diesel engines in this size range, but with a 10:1 weight reduction and a 4:1 improvement in time between overall maintenance. This represents a potential 2:1 increase in fuel efficiency at full power over existing gas turbines in this size range.

KEYWORDS: Shock compression, mobile power plant, future combat systems, fuel cell/rampressor hybrid system

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1. INTRODUCTION

Ramgen Power Systems, Inc. (RPS) is developing two high efficiency gas turbine engine concepts that combine many of the proven features of supersonic compression and expansion systems, commonly used in supersonic flight inlet and nozzle designs, with conventional axial flow turbo-machinery practices to create two entirely new gas turbine engines (Lawlor et al. 2004; Steele et al. 2005). The superior efficiency is a result of high pressure shock wave compression and supersonic expansion phenomena to produce high component efficiencies, and a unique configuration that minimizes flow stream turning losses throughout the engine. The RPS engine concept can be configured as a high pressure ratio simple-cycle design for propulsion applications or as a low pressure ratio recuperated engine, either as a standalone or combined with a fuel cell in a hybrid configuration, for stationary power applications.

The anticipated compression and expansion efficiencies, decreased footprint, and reduced part count of the RPS technologies promise revolutionary new power generation and propulsion systems with deceased heat signatures resulting from lower exhaust temperatures. These unique aerodynamic features will open up new and creative options for engine designers and package integrators that have never been realized or considered.

The stationary power configuration concept can be applied as both a fixed base or forward deployed stationary power generator within all the branch services, and offers excellent efficiency in both standalone power-only mode, or combined with a fuel cell in a hybrid configura-

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tion. Combined Heat and Power (CHP) is an added benefit within either of the arrangement options

The multi-fuel RPS concept promises to revolutionize military and commercial surface, and sea power and propulsion systems, and is scaleable from 225 kWe to 22,500 kWe power requirements. The RPS concept offers the size, weight, and maintenance characteristics of a gas turbine, with the efficiency of a diesel. An ERDC-CERL Technical Report further discusses the technology development and potential applications (Holcomb et al. 2006).

The paper presents the fundamentals of supersonic compression and expansion technology with application to two specific engine cycle configurations: a recuperated cycle 250-400kW microturbine, and a 1000 hp Advanced Supersonic Component Engine. Conceptual engine layouts and performance predictions are included.

2. SHOCK COMPRESSION

Since the sound barrier was broken in the late 1940s, ramjet engines have been widely used as a means to propel aerospace vehicles at supersonic speeds. The technology is very well understood and fully characterized.

All conventional, subsonic jet engines feature discrete compression, combustion, and turbine/expansion sections to create the thrust used to propel an aircraft. In operation, hot pressurized exhaust gas expands through the turbine to drive the compressor, and then further expands through a nozzle, creating forward thrust.

Ramjet engines feature these same discrete compression, combustion, and expansion sections. The significant difference in ramjet engines is that the compressor section does not rotate and the turbine section is therefore eliminated. There are no rotating components in the engine. At supersonic velocities, air is ingested into the engine and flows around a fixed obstructing body in the center of the engine duct, “ramming” the air flow into channels between the center-body and the engine’s sidewall. Inside these channels, the airflow is almost instantaneously slowed to subsonic speeds, creating “shock waves.” These shock waves are associated with a dramatic increase in pressure, or, in other words, “shock compression.” As with conventional subsonic turbine engines, fuel is then added and the hot, pressurized exhaust gas expands through a nozzle to create forward thrust.

Ramjets are simple, with no moving parts, but the aircraft has to be moving at supersonic speeds to initiate the shock necessary for effective operation. As a result, all ramjet experience has been in the context of supersonic planes and missiles. One well-known application of shock compression is its use in the F-15 fighter jet.

3. RAMGEN’S TECHNOLOGY BREAKTHROUGH

Ramgen’s primary technical innovation has been to apply ramjet engine concepts in a stationary compressor application (Figure 1).

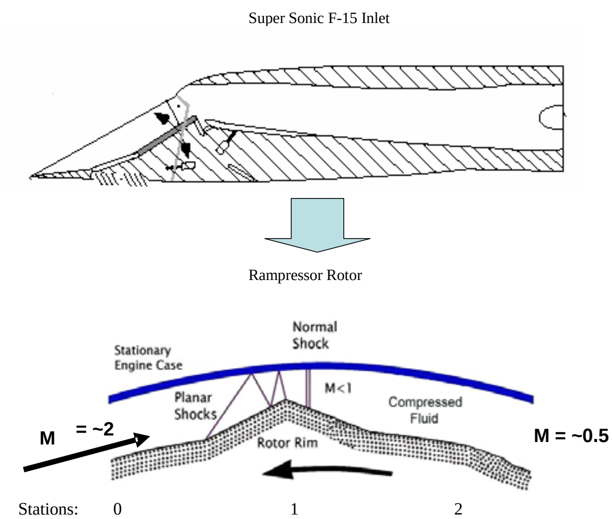

Figure 1. Rampressor Rotor Profile.

Ramgen’s core design, the Rampressor, is a relatively simple device. It features a rotating disk, which operates at the high peripheral speeds necessary to achieve supersonic effect in a stationary environment. The rim of the disk has three raised sections and cavities that mimic the effect of the center-body and channels of a conventional ramjet inlet, depicted in the Rampressor rotor in Figure 2. Air enters through a common inlet and is then ingested into the annular space between the supersonically spinning disk and the outer edge of the casing. When the flow of air enters this space, the raised sections of the disk rim create a “ramming” effect, generating shock waves and air compression in a manner completely analogous to ramjet inlets on supersonic aerospace vehicles. The efficiency of this compression process is very high because the compressor has very few aerodynamic leading edges and minimal drag.

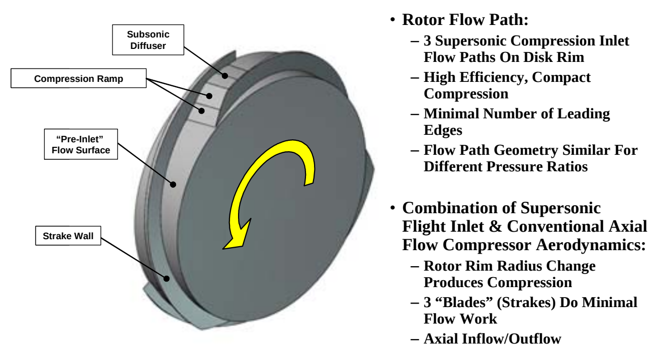

Figure 2. Rampressor rotor.

The disk chambers or “strakes” are angled, so the compressed air is “augured” by rotation into a collector and then on to the intended use. The inherently oil-free compression process requires no oil for lubrication or sealing.

The basic rotor flowpath calculations are relatively simple, as follows:

Stations:
- 0 = inlet conditions
- 1 = throat upstream of normal shock
- 2 = subsonic diffuser exit

Total pressure available in the captured stream tube, P_{t_0} is:

$$P_{t_0} = P_0\left[1+\left(\frac{\gamma-1}{2}\times M_0^{\,2}\right)\right]^{\gamma/\gamma-1} \qquad \text{[Eq. 1]}$$

Available “Relative Pressure Ratio”, $\dfrac{P_2}{P_0}$ is:

$$\frac{P_2}{P_0} = \Pi\times\left[1+\left(\frac{\gamma-1}{2}\right)\times M_0^{\,2}\right]^{\gamma/\gamma-1} \qquad \text{[Eq. 2]}$$

Where total pressure recovery, Π is:

$$\Pi = \frac{P_{t_2}}{P_{t_0}} \cong 1-0.075\times\left(M_0-1\right)^{1.35} \qquad \text{[Eq. 3]}$$

Relative total temperature, T_{t_2} = Constant, is:

$$T_{t_2} = T_{t_0} = T_0\left[1+\left(\frac{\gamma-1}{2}\right)\times M_0^{\,2}\right] \qquad \text{[Eq. 4]}$$

Adiabatic efficiency of the rotating flowpath, η_{ad} is

$$\eta_{ad} = \frac{\left[1+\left(\frac{\gamma-1}{2}\right)\times M_0^{\,2}\right]\times\left[1-0.075\left(M_0-1\right)^{1.35}\right]^{\gamma-1/\gamma}}{\left(\frac{\gamma-1}{2}\right)\times M_0^{\,2}} \qquad \text{[Eq. 5]}$$

The equations are valid for the rotating flowpath, itself. Overall stage efficiency calculations must also include rotor inflow and exit characteristics, modeled in the non-rotating reference frame, which complicates these calculations.

4. EXPANSION – RAM EXPANDER

Just as supersonic flight inlets are commonly used to efficiently decelerate and compress an air stream for use by jet engines, supersonic nozzles are routinely used in ramjet and rocket systems to achieve the expansion and acceleration of gas streams in a wide variety of propulsion systems.

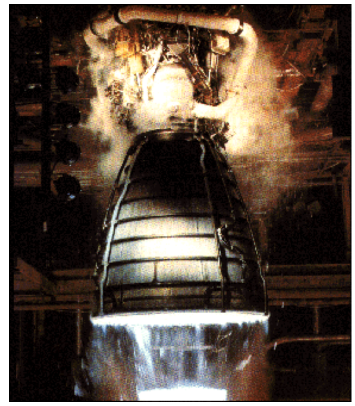

Figure 3. Bell shaped nozzle of shuttle main engine.

Figure 3 shows the Space Shuttle Main Engine (SSME) during a full power test. When operating at its design point, the bell shaped nozzle of this rocket engine efficiently expands the high pressure and high temperature gases in the SSME combustion chamber from 3000 psia to 9 psia, generating a high velocity exhaust stream that is the source of the thrust for the vehicle.

Just as the shock compression features of the supersonic flight inlet were incorporated into the rim of the supersonic compression stage, the planar expansion surface of the supersonic nozzle can be incorporated into the rim of a supersonic expansion stage (Figure 4).

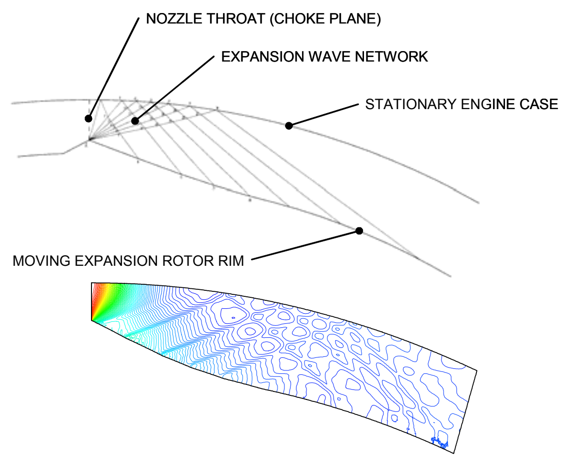

Figure 4. Minimum length planar nozzle designed by the characteristics integrated into rotor rim method.

5. HIGH EFFICIENCY STATIONARY MICRO- AND MINI-TURBINES

Today’s microturbine is nominally a 28% LHV net electric efficiency device and it appears that, as currently designed, the best these units can achieve is 34% (Figure 5). This limits their practical application to Combined Heat & Power (CHP) projects, and as a result, also limits the number of units sold.

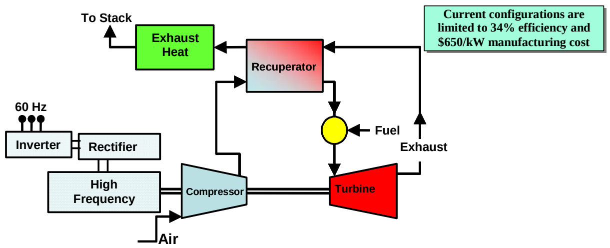

Figure 5. Conventional microturbine layout.

One problem is that these recuperated simple-cycle designs cannot use the full turbine rotor inlet temperature (TRIT) potential because of material cost vs. life limitations on the downstream recuperator. Turbine rotor inlet and exhaust gas temperatures are physically related by turbine efficiency and expansion ratio design values.

The recuperator is a high temperature heat exchanger that serves to re-cycle the waste-heat from the turbine exhaust back to the working fluid after the compressor discharge, and before fuel addition. In current recuperated turbines, the recuperator inlet temperature is at, or very near the metallurgical life limit of 347 stainless steel (SS), the generally preferred material for cost considerations. Alloys such as Inconel 625 have higher temperature capabilities, but they cost approximately three times more per pound than does 347 SS. A switch to such alloys will increase the overall cost of the turbine, which tends to negate the value of any potential efficiency gains.

An approach to avoid high recuperator material costs is to decrease the turbine exhaust temperatures (EGT) by increasing the turbine expansion ratio, as well as turbine efficiency. Recuperated engine configurations (Table 1) show the potential advantages of inserting the Ramgen compressor and expander technology into a microturbine for greater net electric compression efficiency, higher specific power, and lower overall manufacturing costs.

The Rampressor could improve compressor adiabatic stage efficiency from 83 to 88% without exceeding the 347 SS recuperator limit. The potential inclusion of the RAM Expander can further extend these cost and efficiency impacts. Turbine efficiency exerts significant leverage on cycle performance (Table 2), returning approximately 80% of any improvement directly to net electric efficiency. The cycle efficiency and product cost impacts could yield efficiencies close to the best high temperature fuel cells at 44-50% levels.

Ramgen contracted with Brayton Energy to investigate the mechanical design of a turbine based on Ramgen technology and to assess the impact on the fuel cell hybrid system efficiency. Several configurations were assessed for a range of pressure ratios. Rampressor compressor nominal geometry and efficiency, as well as industry standard values for recuperator and uncooled metal turbine efficiencies formed the basis for the mechanical layout and performance evaluation.

Brayton Energy's initial findings indicate that a three-stage axial turbine best matches the Rampressor design point specific speed. The design point efficiency for the 220 kW unit, is 35.4% based on a three-stage axial turbine. The Rampressor with a conventional axial turbine results in an efficiency improvement over conventional microturbine configurations. However, it was determined that the specific speed of the Rampressor could be better matched with a rotating super-sonic nozzle turbine, or Ram Expander. The notional Ram Expander performance was developed and used to assess efficiency improvements in both the microturbine and the pressurized Solid Oxide Fuel Cell hybrid system. Table 2 lists the results for the microturbine, where the current design point of reference is the Rampressor with a conventional three-stage axial turbine.

Ramgen has proposed a design for a breakthrough gas turbine configuration with projected efficiencies of 43-45%. This projected efficiency achieves a 50% improvement over the "best of class" comparably sized small turbines, and is comparable to the projected 40-42% full-load efficiency of both high temperature molten carbonate fuel cell technology, and approaching the efficiency of a solid oxide fuel cell at 46-49%. Ramgen intends to offer a RAM-Turbine configuration that incorporates its supersonic compressor, Advanced Vortex Combustor (AVC) and expander technologies in the 250-400kW range, low pressure ratio, recuperated cycle gas turbine. The engine will be a single spool configuration (Figures 6 and 7).

Table 1. Potential advantages of Ramgen technology in recuperated engines.

		Rampressor		Rampressor & RAM-Expander	
	Current	All Metal	Ceramic Rotor	All Metal	Ceramic Rotor
Mass Flow - lbm/s	3.0	3.0	3.0	3.0	3.0
Pr:1	3.8	5.7	6.3	4.7	5.1
TRIT - °F	1638	1800	2200	1800	2200
EGT - °F	1185	1185	1400	1185	1400
Compressor %	83.0%	88.0%	88.0%	88.0%	88.0%
Turbine %	85.0%	85.0%	85.0%	92.0%	92.0%
Net Electric %	34.2%	38.0%	44.8%	43.8%	49.9%
kW	160	231	364	268	408
Mfg Cost/kW	$650	$451	$307	$417	$296
Cost	$104,268	$104,268	$112,010	$112,010	$120,995
Recup $/kW	$80	$54	$51	$54	$53
	$12,833	$12,507	$18,750	$14,513	$21,757
Material Cost					
347SS	$4,278	$4,169		$4,838	
$/lb	$3.50	$3.50		$3.50	
INCO 625			$11,912		$13,822
$/lb			$10.00		$10.00
Mtl Δ			$7,743		$8,984

Table 2. Benefit of ram expander performance on Rampressor with conventional turbine.

	NS c	TIT (F)	RIT(F)	turbine efficiency	power (kW)	LHV efficiency	HHV efficiency	notes
**Current Design Point	0.45	1700	1013	84.4%	220.1	35.4%	31.8%	- Rampressor parameters from map design point - Quoted turbine efficiency requires 3 stages
Current Design Point + higher Rampressor NS	0.60	1700	1013	84.4%	402.8	35.8%	32.3%	- Rampressor upflowed to NS=0.60 - Comparable turbine efficiency achievable in 2 stages
Current Design Point + higher Rampressor NS + increased turbine effy	0.60	1700		88.2%	444.6		34.3%	- 3 stg turbine more efficient at higher Rampressor NS - 1 pt tubine effy yeilds +2.7% power & 0.6 pts effy
Current Design Point + higher TIT	0.45	1953	1200	84.4%	284.3	39.6%	35.6%	- 2 stg turbine - Low turbine tip speed gives opportunity for ceramics - Max TIT corresponds to RIT=1200F (stainless recup)
Current Design Point + higher TIT + higher Rampressor NS	0.60	1953	1200	84.4%	518.6	40.0%	36.0%	- 2 stg turbine
Current Design Point + higher TIT + higher Rampressor NS + higher turbine effy	0.60	2000	1200	88.2%	588.4	42.7%	38.4%	- 3 stg turbine - higher turbine efficiency gives increased delta T
Ram Expander Turbine	0.45	1700 to 2000		93.0%	220	~40.8% to 45.2%	36.7% to 40.7%	

*Power & efficiency are gross electric and do not reflect fuel booster or accessory loads
**Current Design Point = Rampressor with three-stage axial turbine

* Rampressor fixed at 90% efficienciey and 7.6 PR for all cases

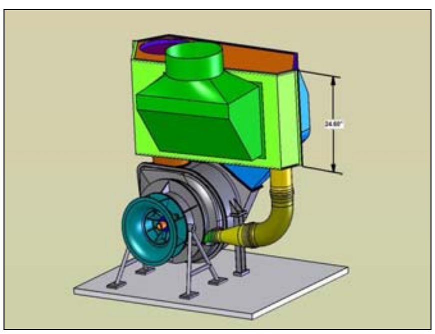

Figure 6. Ram-Turbine system.

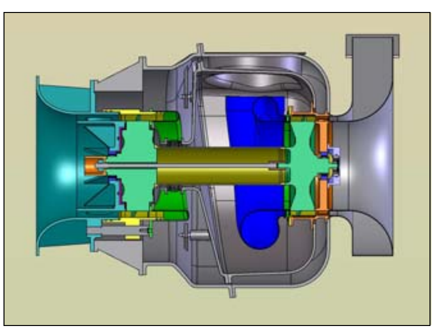

Figure 7. Ram-Turbine details.

Product ratings and component sizing are still being determined, but the goal is to achieve some level of cross-platform component sharing with the Advanced Supersonic Component Engine (ASCE), described in the next section, as a method to leverage development cost and eventually, manufacturing and field inventory. As such, the ratings and specific dimensions will change as these efforts continue to evolve. The RAM-Turbine is intended to support independent operation in either a simple PowerGen or Combined Heat & Power (CHP) configurations, as well as to operate as part of either a direct or an indirect hybrid fuel cell system.

6. ADVANCED SUPERSONIC COMPONENT ENGINE (ASCE)

The gas turbine has always been the preferred alternative for marine propulsion applications, offering superior size, weight, and maintenance advantages over reciprocating diesel engines, but it has been unable to compete at power levels less than 10MW, primarily due to its high fuel consumption.

At the same time, larger aero-derivative gas turbines are successfully applied at 25MW and above where the size and weight of diesel engines is prohibitive, despite the fact that the fuel consumption of the turbine is, at best, considered a compromise. Improvements in efficiency of these engines to the 40% level have been achieved through increases in both pressure ratio and firing temperature, which also results in a growth in rated engine output.

The ASCE concept was originally conceived as a single rotor with all the engine components included on the rim. This privately funded work was the first engine configuration Ramgen explored. Although supersonic compression and expansion aerodynamics and high-swirl/high velocity stabilized combustion are fundamentally well established, these technologies have never been integrated into one cycle for generating shaft power.

Ramgen's concept was refined and improved to retain the superior performing rotating components such as compression and expansion while reconfiguring other components such as combustion to maximize producability and maintainability. Four technologies make up the ASCE:

- Rotating supersonic compressors
- High velocity flow combustor
- Rotating supersonic expanders
- Direct connect to high speed PM electric generator/motor.

The multi-fuel ASCE concept promises to revolutionize military and commercial land-based and sea power propulsion systems and is scaleable from 300 hp to 30,000 hp shaft power requirements. The scalability of the ASCE will make it competitive in both the diesel and gas turbine markets. RPS is proposing a 1000 hp demonstration program as a popular rating with immediate Naval manned and unmanned combatant craft applications and a size that would offer a manageable financial exposure.

Additional military opportunities that have been identified are Army TACOM/TARDEC hybrid vehicles, USAF airborne electric power generation systems for the directed energy weapons systems and all branches of the USSOCOM. The engine can also be applied as both a fixed base or forward deployed stationary power generator within all the branch services.

The Defense Advanced Research Projects Agency (DARPA) awarded a "seedling" contract to Ramgen Power Systems to complete the notional design definition and layout of its proposed ASCE concept. The purpose of the project is to deliver a new engine that will meet future DOD requirements for long endurance, high efficiency, and long time-between-overhaul power generating and propulsion applications.

The proposed 1000 hp engine for DARPA is a two stage counter-rotating, 30:1 pressure ratio, ~40% simple-cycle efficient engine that drives a high-speed direct drive permanent magnet (PM) electric generator/motor, as shown in Figure 8, for either electric power generation or hybrid vehicle propulsion applications. The multi-fuel ASCE system promises a Specific Fuel Consumption (SFC) equal to or better than the fuel consumption of current reciprocating diesel engines in this size range, but with a 10:1 weight reduction and a 4:1 improvement in time-between-overall maintenance. This is a 2:1 increase in fuel efficiency at full power over existing gas turbines in this size range. Pressure ratios of 40:1 with ~45+% cycle efficiencies are considered feasible growth engine objectives.

The ASCE concept integrates supersonic shock compression and expansion systems into a high pressure ratio, compact, high efficiency Brayton simple-cycle engine. The system thermal efficiency for existing Brayton Cycle, land-based and flight engine systems increases as the design Turbine Inlet Temperature (TRIT) increases. The current recipe for increasing gas turbine efficiency has been, and likely will remain, to increase the turbine firing temperature (TRIT), which focuses much of the research and development effort on increases in high temperature materials capability. For each TRIT, however, and for a given set of component efficiencies, there is also an optimum pressure ratio (OPR) to achieve either maximum thermal efficiency or maximum power density.

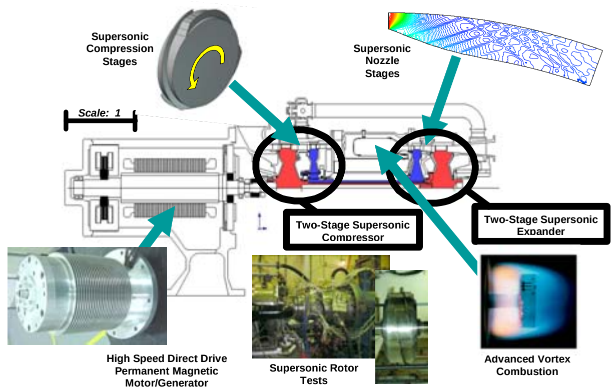

Figure 8. Two spool ASCE concept.

The important understanding from such analyses is that pressure ratio typically rises along with increases in TRIT. This does improve the efficiency, but it also increases engine power. The result of this is that there are no gas turbine engines available at the lower power levels and diesels predominate in these applications. Figure 9 shows a plot of those same land-based and flight engines plotted vs. engine rated power, and as can be seen, there are no small <u>and</u> efficient gas turbines.

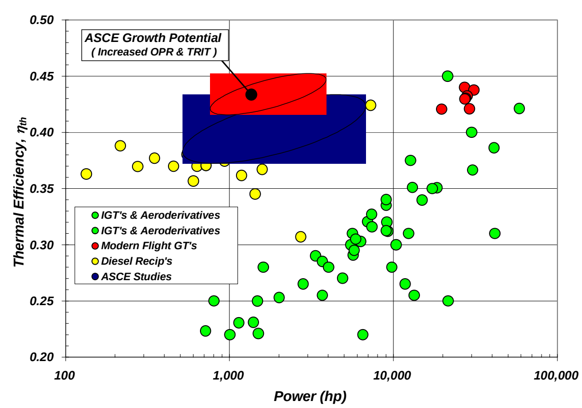

Figure 9. Thermal efficiency vs. rated power.

The ASCE engine concept is also shown on the same plot, indicating the potential for this engine to compete with small diesels. Diesel engines are not purchased on

preference, but they offer the best value in these sizes, even though their emissions, size, weight, and maintenance costs are considered serious negatives.

As a result, the ASCE engine offers the promise of diesel engine efficiency with the size, weight, and maintenance attributes of a gas turbine, as indicated in Figure 10 below, which compares the efficiencies of existing gas turbines under 5000 hp and the proposed ASCE 1000 hp engine, indicating a factor of 2x improvement in efficiency.

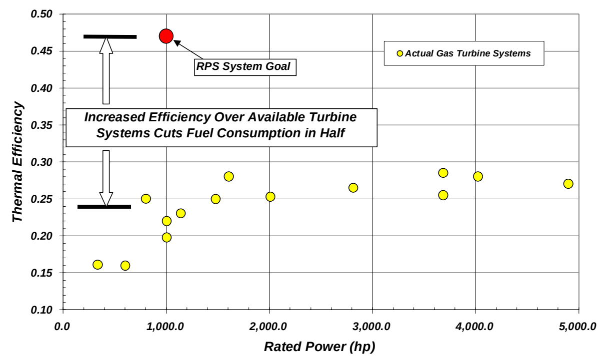

Figure 10. Efficiencies of existing gas turbines under 5000 hp and those of proposed ASCE 1000 hp engine.

The two-spool simple-cycle configuration may also allow Ramgen to configure the system with two different power settings, to better match the specific mission profiles. Many of the military applications feature both a loitering power level and a maximum power level. Figure 11 shows the use of these two spools and its impact on overall engine performance. The cross-over point can be tailored to specific applications by altering the respective pressure ratio split between the spools.

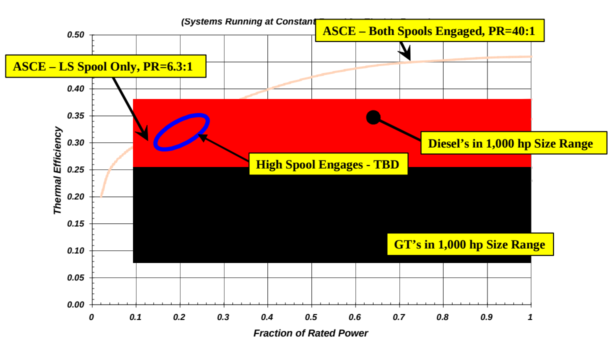

Figure 11. Use of loitering power level and a maximum power level and the impact on overall engine performance.

While the lower power fuel economy is of great interest, some of these applications require that full power be available instantaneously. Ramgen is exploring concepts that would provide a unique capability to satisfy these requirements.

7. CONCLUSION

Ramgen Power Systems has developed three fundamental technology platforms intended to improve the cost and performance of gas turbine engines and gas turbine based systems. These components can be configured to address specific applications for stationary power generation, or hybrid-electric drive and/or auxiliary power units.

Two such configurations have been presented in his paper: A recuperated cycle 250-400kW microturbine; and a 1000 hp Advanced Supersonic Component Engine. Other application configurations and derivative products are well within the reach of these technologies, and can offer similar and compelling benefits as well as unique approaches and solutions to challenging problems. Figure 12 shows a technology roadmap that provides an insight into those combinations and possibilities.

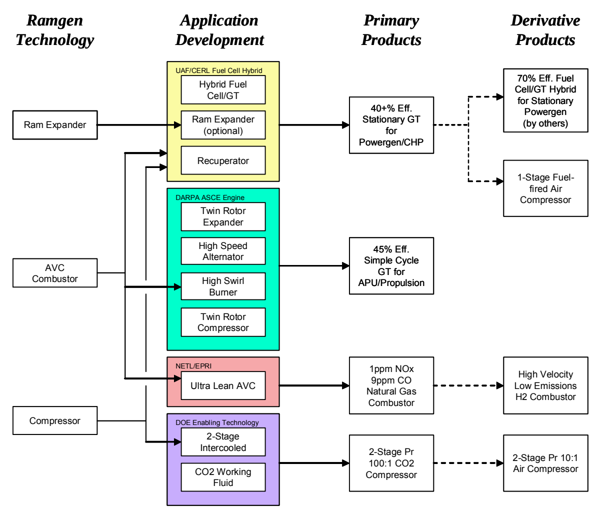

Figure 12. Ramgen technology development roadmap.

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